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**AERODYNAMIC DESIGN OPTIMIZATION WITH
SENSITIVITY ANALYSIS AND COMPUTATIONAL FLUID
DYNAMICS**

By

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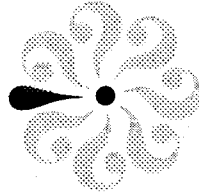
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AERODYNAMIC DESIGN OPTIMIZATION WITH SENSITIVITY ANALYSIS AND COMPUTATIONAL FLUID DYNAMICS

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§.1 Introduction

An investigation was conducted from October 1, 1990 to May 31, 1994 on the development of methodologies to improve the designs (more specifically, the shape) of aerodynamic surfaces by coupling optimization algorithms (OA) with Computational Fluid Dynamics (CFD) algorithms via sensitivity analyses (SA). The study produced several promising methodologies and their proof-of-concept cases, which have been reported in the open literature.

One of the developed design optimization methodologies has received two *Certificates of Recognition* from NASA ("for disclosing an inventive contribution," 1992, and "for the creative development of a scientific contribution which has been determined to be of significant value in the advancement of NASA's aerospace technology program," 1993). Also, a *patent application* has been filed for this design method.¹

After providing a background for the topic, only a very brief overview of the research supported under NAG-1-1188 is given in §.2. However, the details are available in the technical publications listed in §.3. and sampled by cover pages in §.4.

§.2 Overview

Aerodynamic design of an aircraft or its components may be performed by one of several approaches. Computationally, however, the approaches are either done by an *inverse* method or a *direct* method. Although each has its own merits, the direct numerical

optimization methods enjoy the advantage of working towards an easily identifiable objective without the need to specify any *target* designs or shapes. Specifying such targets requires a database, which may not always be available, particularly, for complex configurations with aerodynamically interfering components.

The accuracy of the optimization method in search of better designs and the efficiency with which it can accomplish this, are directly related to the accurate and efficient receipt of the *gradient information* on the objectives and the constraints; that is, the sensitivity coefficients. This has been the differentiating factor between the many direct optimization approaches currently being studied.

Sensitivity coefficients can be delivered to the optimizer through *sensitivity analysis*, which often refers to the quasi-analytically obtained sensitivities, rather than the traditional finite-differences approach. To this end, the governing equations of fluid flow can be differentiated analytically either after they have been CFD-discretized (*discrete* sensitivity analysis), or starting with their original differential form and using the variational concepts (*variational* sensitivity analysis, which is also known as either continuous method, or adjoint formulation, or control theory approach).

First, an aerodynamic sensitivity analysis method² was developed for the first-order discretized, compressible, two-dimensional Euler equations. This method was then used to couple an optimization package, ADS,³ with a CFD package, CFL3D,⁴ and applied to the design (by changing ramp and cowl angles only) of a scramjet-afterbody configuration to optimize its axial thrust.⁵ The scramjet-afterbody was again used to validate an extension of the method⁶ to the higher-order discretization of the Euler equations, which is up to third-order accurate. In this study, three different initial shapes of the ramp were used in three independent optimizations, all of which converged to virtually the same final shape. Viscous effects were later accounted for by including the sensitivities of the thin-layer Navier-Stokes equations and demonstrated by optimizing a transonic airfoil.⁷

The status of the developments presented at the Computational Aerosciences Conference of NASA⁸ and the algorithmic developments were presented to several communities with interests in the computational and applied mathematics⁹⁻¹¹.

Then, the issue of computational-time efficiency was addressed in several ways,¹² including the surface parameterization using Bezier splines and Bernstein polynomials, and

solving the unfactored CFD equation by a quasi-Newton's method. In an effort to isolate the effects of such algorithmic improvements, a separate computer code was developed, which did not include CFL3D, and had several other consistency features, such as, the implicit treatment of the boundary conditions. The computer storage efficiency was later addressed¹³ by examining the solution of the sensitivity equation as well as the CFD equation using a conjugate-gradient like method, known as the (restarting version) generalized minimum residual [GMRES(k,m)] method, as compared to a direct inversion method. The status of the project was then detailed in a report.¹⁴

In addition, the investigation was turned to the development of the *multiblock sensitivity analysis scheme* called SADD.¹⁵ This scheme was motivated by the need to address the computer memory issues in the direct inversion of the sensitivity equation's coefficient matrix, which becomes particularly large. Another important benefit was its applicability to problems involving complex and multicomponent geometries, around which structured grids can only be generated by the use of domain decomposition techniques. The additional and potential advantages of this approach were: (i) its amenability to parallel processing, (ii) demonstration (without the implementation) of a method for non-hierarchical, multidisciplinary sensitivity analysis, where the sensitivities are coupled. The SADD scheme was later extended to three dimensions, where GMRES(k,m) was also incorporated.¹⁶

Along with the shape optimization studies, a multi-stage, wing-shape optimization method was developed and demonstrated for a transport wing.¹⁷ The method first designs the planform of a wing, then shapes its sections for the twist and camber.

Finally, a design optimization method based on the variational methods has also been studied and a proof-of-concept study was conducted for a quasi-one-dimensional duct flow¹⁸. Preliminary studies indicated that the method was capable of handling all flow regimes with or without shocks. In the variational sensitivity analysis approach, the sensitivity coefficients are produced by putting the perturbations of the dependent variables in the governing differential equations of the fluid flow. The *co-state* equations (or the *adjoint* equations) derived in this manner are partial differential equations, which are of the same order and character as the flow equations.

Before closing this summary, two more important points should be made. First, as a grant of a research project conducted by an academic team, NAG-1-1188 has also provided

financial support, either partially (along with one of the following grants: NAG-1-811, NAG-1-1499, NAG-1-1576) or fully, to two Ph.D. students,^{19,20} one Master's student,²¹ and a post-doctoral research associate. A third Ph.D. study²² was terminated before its completion. Secondly, the results of the present investigation has laid the foundation to two follow-up projects currently being supported under other grants (NAG-1-1499 and NAG-1-1576). The former is a graduate programs fellowship^{21,23}, but the latter project focuses on algorithms, tools, and applications directed toward a supersonic transport plane²⁴⁻²⁵.

Summarized in Table 1 are the aerodynamic examples used to demonstrate the capabilities of the present investigation.

§.3 References

1. CADOSA (Computational Aerodynamic Design Optimization using Sensitivity Analysis), NASA Case LAR 14815-1-CU, *Patent* Serial No. 07 / 820,432 June 1992. (support under NAG-1-1188)
2. Baysal, O., and Eleshaky, M.E., "Aerodynamic Sensitivity Analysis Methods For the Compressible Euler Equations," *Recent Advances in CFD*, ASME-FED Vol. 103 (Ed.: O. Baysal), Dallas, TX, Nov. 1990. Also, [ASME] *Journal of Fluids Engineering*, Vol. 113, No. 4, Dec. 1991, pp. 681-688. (support under NAG-1-1188)
3. Vanderplaats, G.N., "ADS - A FORTRAN Program for Automated Design Synthesis - Version 1.10," NASA Contractor Report 177985, Sept. 1985.
4. Thomas, J.L., Krist, S.T., and Anderson, W.K., "Navier-Stokes Computations of Vortical Flows Over Low Aspect Ratio Wings," *AIAA Journal*, Vol. 28, No. 2, Feb. 1990, pp. 205-215.
5. Baysal, O., and Eleshaky, M.E., "Aerodynamic Design Optimization Using Sensitivity Analysis and Computational Fluid Dynamics," AIAA Paper 91-0471, AIAA 29th Aerospace Sciences Meeting, Reno, NV, Jan. 7-10, 1991. Also, *AIAA Journal*, Vol. 30, No. 3, Mar. 1992, pp. 718-725. (support under NAG-1-1188)
6. Baysal, O., Eleshaky, M.E., and Burgreen, G.W., "Aerodynamic Shape Optimization Using Sensitivity Analysis on Third-Order Euler Equations," AIAA Paper 91-1577 CP, *Proceedings of 10th Computational Fluid Dynamics Conference*, Honolulu, HI, June 1991. Also, *Journal of Aircraft*, Vol. 30, No.6, Nov./Dec. 1993, pp. 953-961. (support under NAG-1-1188)
7. Eleshaky, M.E. and Baysal, O., "Airfoil Shape Optimization Using Sensitivity Analysis on Viscous Flow Equations," *Multidisciplinary Applications of CFD*, ASME-FED Vol. 129 (Ed.: O. Baysal), Atlanta, GA, Dec. 1991. Also, [ASME] *Journal of Fluids Engineering*, Vol. 115, No. 1, Mar. 1993, pp. 75-84. (support under NAG-1-1188)

8. Baysal, O., Eleshaky, M.E., and Burgreen, G.W., "Aerodynamic Design Optimization Using Sensitivity Analysis and CFD," *Compendium of Abstracts, Computational Aerosciences Conference*, NASA Ames Research Center, August 1992, pp. 22-25. (support under NAG-1-1188)
9. Baysal, O., Eleshaky, M.E., and Burgreen, G.W., "New and Efficient Methods for Aerodynamic Shape Optimization," International Conference on Inverse Design Concepts and Optimization in Engineering Sciences (ICIDES III), Washington, D.C. Oct. 23-25, 1991. (support under NAG-1-1188)
10. Eleshaky, M.E. and Baysal, O., "An Optimization Procedure Using Sensitivity Analysis and CFD," *Proceedings of 2nd International Conference on Industrial and Applied Mathematics* (ICIAM), Washington, DC., Jul. 8-12, 1991, p. 63. (support under NAG-1-1188)
11. Baysal, O., Eleshaky, M.E., and Burgreen, G.W., "Coupling CFD with Optimization via Discrete Sensitivity Analysis," Proceedings of 2nd US National Congress on Computational Mechanics, Aug. 16-18, 1993, Washington, D.C., p. 128. (support under NAG-1-1188)
12. Burgreen, G.W., Baysal, O., and Eleshaky, M.E., "Improving the Efficiency of Aerodynamic Shape Design Procedures," AIAA Paper No. 92-4697 CP, *Proceedings of 4th AIAA/AIRFORCE/NASA/OAI Multidisciplinary Analysis and Optimization Conference*, Cleveland, OH, Sep. 1992. Also, *AIAA Journal*, Vol. 32, No. 1, Jan. 1994, pp. 69-76. (support under NAG-1-1188)
13. Burgreen, G.W., Baysal, O., "Aerodynamic Shape Optimization Using Preconditioned Conjugate Gradient Methods," AIAA Paper No. 93-3322 CP, *Proceedings of 11th Computational Fluid Dynamics Conference*, Orlando, FL, Jul. 1993. Also, *AIAA Journal*, Vol. 32, No. 11, Nov. 1994, pp. 2145-2152. (support under NAG-1-1188)
14. Baysal, O., "Flow Analysis and Design Optimization Methods for Nozzle-Afterbody of a Hypersonic Vehicle," *NASA -CR-4431*, April 1992. Also, *Computational Methods in Hypersonic Aerodynamics* (Ed.: T.K.S. Murthy), Ch. 10, pp. 341-386, Computational Mechanics Publications, Kluwer Academic Publishers, Southampton, U.K., 1992. (support under NAG-1-1188 and NAG-1-811)
15. Eleshaky, M.E. and Baysal, O., "Aerodynamic Shape Optimization via Sensitivity Analysis on Decomposed Computational Domains," AIAA Paper No. 92-4698 CP. *Proceedings of 4th AIAA/AIR FORCE/NASA/OAI Multidisciplinary Analysis and Optimization Conference*, Cleveland, OH, Sep. 1992. Also, *Journal of Computers and Fluids*, Vol. 23, No. 4, May 1994, pp. 595-611. (support under NAG-1-1188)
16. Eleshaky, M.E., and Baysal, O., "Preconditioned Domain Decomposition Scheme for 3-D Aerodynamic Sensitivity Analysis," *Proceedings of 11th AIAA CFD Conference*, Orlando, FL, July 1993, pp. 1055-1056. Also, *AIAA Journal*, Vol. 32, No. 12, Dec. 1994. (support under NAG-1-1188)
17. Burgreen, G.W., and Baysal, O., "3-D Aerodynamic Shape Optimization of Wings Using Sensitivity Analysis," AIAA Paper 94-0094, AIAA 32nd Aerospace Sciences Meeting, Reno, NV, Jan. 1994. Also, to appear in *AIAA Journal*. (support under NAG-1-1188)

18. Ibrahim, A.H., and Baysal, O., "Design Optimization Using Variational Methods and CFD," AIAA Paper 94-0093, AIAA 32nd Aerospace Sciences Meeting, Reno, NV, Jan. 1994.(support under NAG-1-1188)
19. Eleshaky, M.E., "A Computational Aerodynamic Design Optimization Method Using Sensitivity Analysis," *Ph.D. Thesis* , Old Dominion University, May 1992.(support under NAG-1-811 and NAG-1-1188)
20. Burgreen, G.W., " 3-D Aerodynamic Shape Optimization Using Sensitivity Analysis," *Ph.D. Thesis* , Old Dominion University, May 1994. (support under NAG-1-1188 and NAG-1-1576)
21. Lacasse, J.M., " Implementation of a Multiblock Sensitivity Analysis Method in Numerical Aerodynamic Shape Optimization," *M.S. Thesis* , Old Dominion University, May 1994. (support under NAG-1-1188 and NAG-1-1499)
22. Ibrahim, A.H., "Variational Sensitivity Analysis," incomplete Ph.D. dissertation study, 1994. (support under NAG-1-1188)
23. Lacasse, J.M., and Baysal, O., "Shape Optimization of Single- and Two-Element Airfoils on Blocked Grids," AIAA Paper 94-4273, *Proceedings of 5th AIAA/USAF/NASA/ISSMO Multidisciplinary Analysis and Optimization Conference*, Panama City, FL, Sept. 1994, pp. 108-116. Also, submitted to *Journal of Inverse Problems in Engineering*. (support under NAG-1-1188 and NAG-1-1499)
24. Eleshaky, M.E., and Baysal, O., "Design of 3-D Nacelle Near Flat-Plate Wing Using Multiblock Sensitivity Analysis (ADOS)," AIAA Paper 94-0160, AIAA 32nd Aerospace Sciences Meeting, Reno, NV, Jan. 1994. Also, to appear in *Journal of Aircraft*.. (support under NAG-1-1188 and NAG-1-1576)
25. Burgreen, G.W., and Baysal, O., "Three-Dimensional Aerodynamic Shape Optimization of Delta Wings," AIAA Paper 94-4271, *Proceedings of 5th AIAA/USAF/NASA/ISSMO Multidisciplinary Analysis and Optimization Conference*, Panama City, FL, Sept. 1994, pp. 87-97. (support under NAG-1-1188 and NAG-1-1576)

§.4. Cover pages of sample publications

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Aerodynamic Sensitivity Analysis Methods for the Compressible Euler Equations

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A mathematical formulation is developed for aerodynamic sensitivity coefficients based on a discretized form of the compressible, two-dimensional Euler equations. A brief motivating introduction to the aerodynamic sensitivity analysis and the reasons behind an integrated flow/sensitivity analysis for design algorithms are presented. Two approaches to determine the aerodynamic sensitivity coefficients, namely, the finite difference approach, and the quasi-analytical approach are discussed with regards to their relative accuracies and involved computational efforts. In the quasi-analytical approach, the direct and the adjoint variable methods are formulated and assessed. Also, several methods to solve the system of linear algebraic equations, that arises in the quasi-analytical approach, are investigated with regards to their accuracies, computational time and memory requirements. A new flow prediction concept, which is an outcome of the direct method in the quasi-analytical approach, is developed and illustrated with an example. Surface pressure coefficient distributions of a nozzle-afterbody configuration obtained from the predicted flow-field solution are compared successfully with their corresponding values obtained from a flowfield analysis code and the experimental data.

Introduction

Computational fluid dynamics (CFD) has recently evolved to a level of maturity to simulate complex flows with reasonable fidelity to the flow physics. Among many reasons responsible for this emergence of CFD, probably the most important one, is the increased accessibility and hence the wide spread use of the supercomputers with high computing speeds and large memories. The aerodynamic design now more than ever enjoys the results of CFD as an important part of its database. An illustration of the major reasons which push and pull CFD to design is given in Fig. 1.

Often the dilemma a designer is challenged with, however, is the conflicting targets derived from isolated CFD analyses for the individual components of an aircraft. An obvious remedy, whenever it is possible, is a combined analysis of the aerodynamics of an integrated structure. Examples for this include the airframe-propulsion integration (Murthy and Paynter, 1986) and the aircraft-stores integration (Baysal et al., 1991a). An important outcome of such an approach is the aerodynamic interference between the components. A drawback, however, is the prohibitively high cost of performing flow analyses for a large matrix of parameters associated with a complex, multicomponent configuration.

With this impetus, it is desirable to know the aerodynamic sensitivity of the instantaneous design to all the involved parameters and thereby reduce the analysis matrix to include only

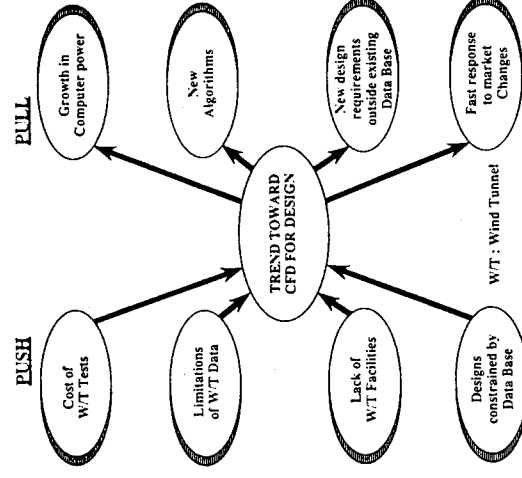


Fig. 1 The factors which push and pull the trend toward CFD for design (Murthy and Paynter, 1986)

the parameters deemed most influencing. Also, a design optimization algorithm requires the first-order gradients of the objective and the constraint functions. Determination of these gradients necessitates the aerodynamic sensitivity coefficients, that is, the derivatives of the objective and the constraints with respect to the design variables. Since in most optimization

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